QCD Physics with
Ultra-relativistic Nuclear Collisions

Compelling Physics at RHIC illuminating Strong Interactions

What are the Fundamental Questions?

How have RHIC's Discoveries shaped and sharpened them?

Future directions as RHIC shifts from
its <u>discovery</u> phase
to its <u>quantitative exploratory</u> phase

QCD is the first fundamental theory based on unobservable mathematical objects (quarks and gluons)

However, QCD gives experimentally falsifiable predictions for how 99.9% of the visible (nuclear) mass of the universe should behave

This Theory must be tested with increasing precision over the widest dynamic range with ***e^- + A , p + A, B + A (A= 1 – 238 and √s)***

JLab, HERA, (eRHIC)	RHIC, (RHIC-II, LHC)	World Class Nuclear Physics

As with QED high T_c superconductors, experiment must also lead the way in the discovery and exploration of new states of QCD matter

Novel theoretical possibilities:

Quark-Gluon Plasma, Color Glass Condensate, Color Superconductivity
Density Isomers, Pion Condensates, Disordered Chiral Codensates

Discoveries require advanced experimental facilities and detectors and a generous helping of "good luck" from Nature

The Predicted Equation of State of QCD matter

Lattice QCD

F.Karsch et al, PLB 478 (00) 477

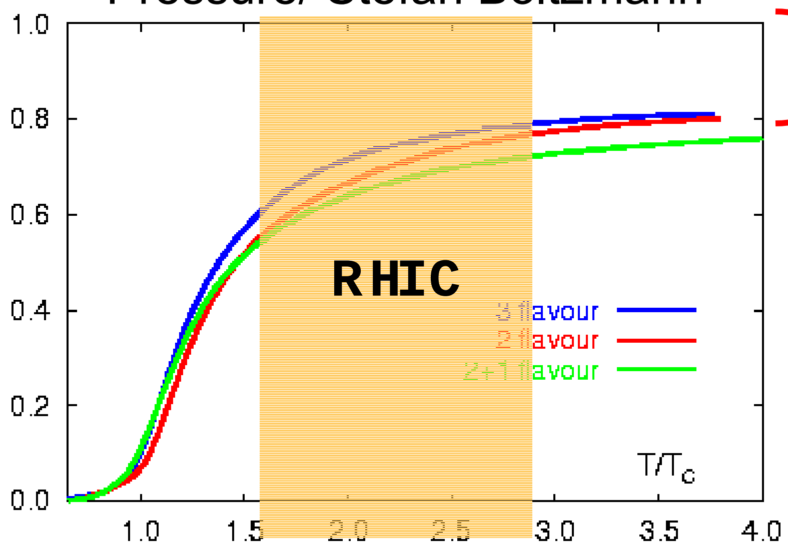
T_c~160-170 MeV

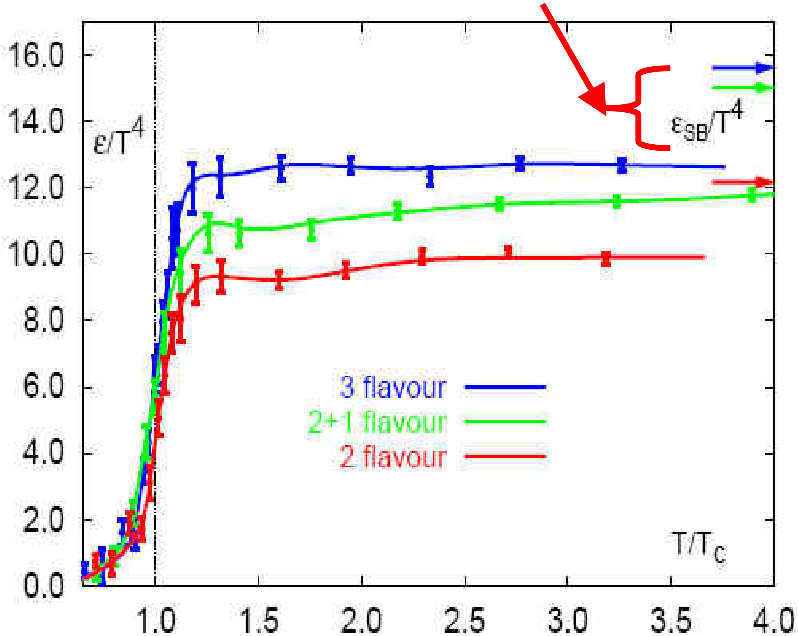
Pressure $P_{QCD}(T)$

Seems perturbative for $T > T_c$

Only 20% deviation from ideal gas

Pressure/ Stefan Boltzmann

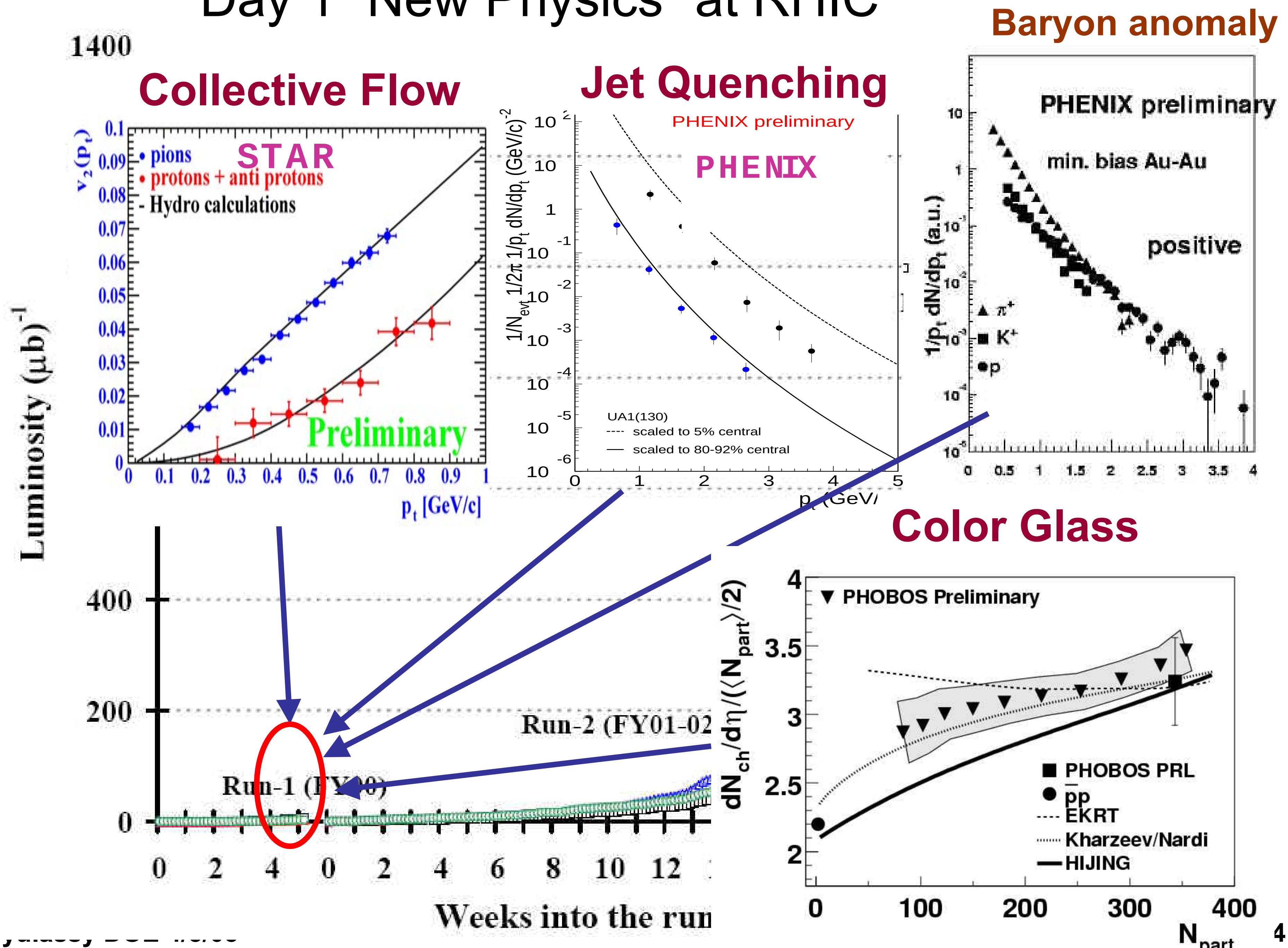


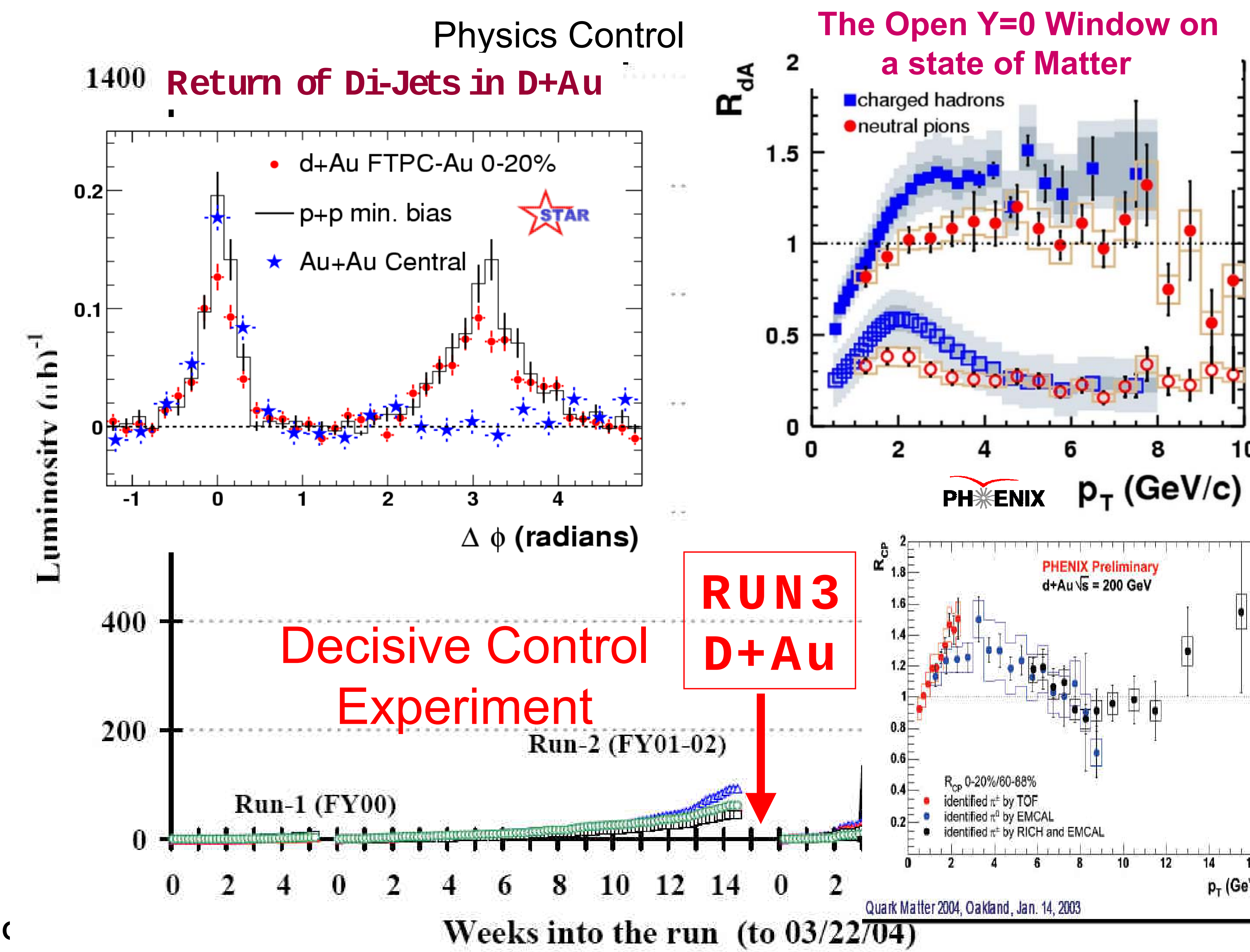


Suggests that Quark Gluon Plasma above T_c

Could be weakly coupled = wQGP !

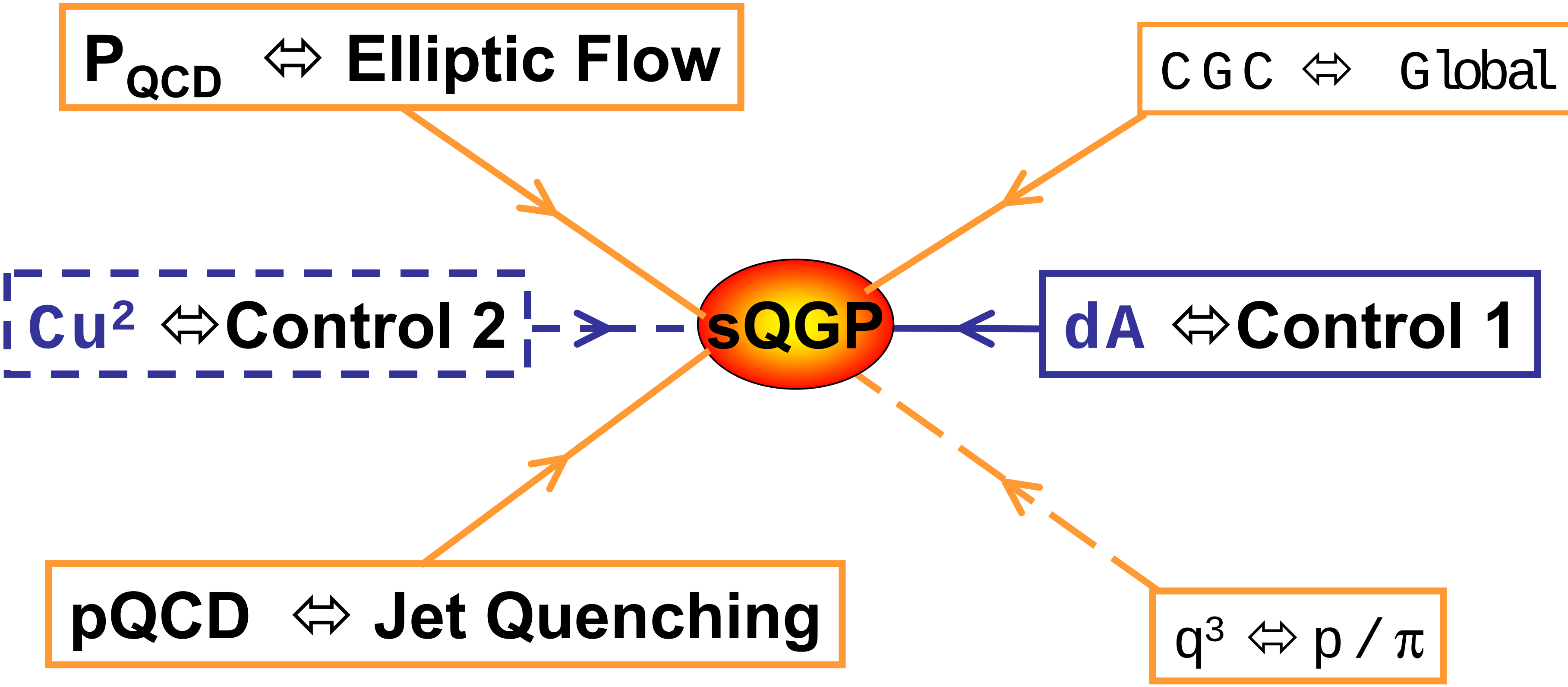
Day 1 "New Physics" at RHIC





Physics Control
Return of Di-Jets in D+Au
d+Au FTPC-Au 0-20%
p+p min. bias
Au+Au Central
STAR
Δ φ (radians)
Luminosity (μb)-1
The Open Y=0 Window on a state of Matter
charged hadrons
neutral pions
R_{dA}
PHENIX
p_T (GeV/c)
Decisive Control Experiment
RUN3 D+Au
Run-1 (FY00)
Run-2 (FY01-02)
Weeks into the run (to 03/22/04)
PHENIX Preliminary
d+Au $\sqrt{s}$ = 200 GeV
R_{CP} 0-20%/60-88%
identified $\pi^{\pm}$ by TOF
identified π^0 by EMCAL
identified $\pi^{\pm}$ by RICH and EMCAL
R_{CP}
p_T (GeV/c)
Quark Matter 2004, Oakland, Jan. 14, 2003

Empirical Evidence at RHIC that points to the Discovery of sQGP and CGC



$$sQGP = P_{QCD} + pQCD + dA + Q_s + q^3 + Cu^2$$

$$CGC = Q_s(y,A)$$

Theoretical tools used at RHIC are built on rigorous limits of the Standard Model

1. Asymptotic free perturbative pQCD
   Proton Spin structure (high Q > 2 GeV)
   Jets and heavy quarks (high p_T> 10 GeV)

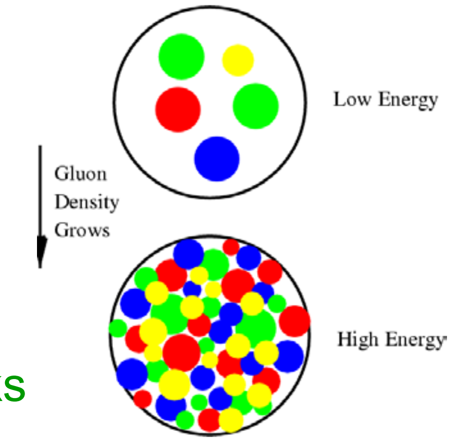
2. High temperature/density thermodynamics
   nonperturbative Lattice QCD
   Long Wavelength Collective (low p_T < 1 GeV)

3. High energy light cone QCD
   Color Glass Condensate (small x< 0.001)

Fundamental Questions about the Strongest Force of Nature that Ultra-relativistic nuclear collisions (p+p, p+A, B+A) may answer

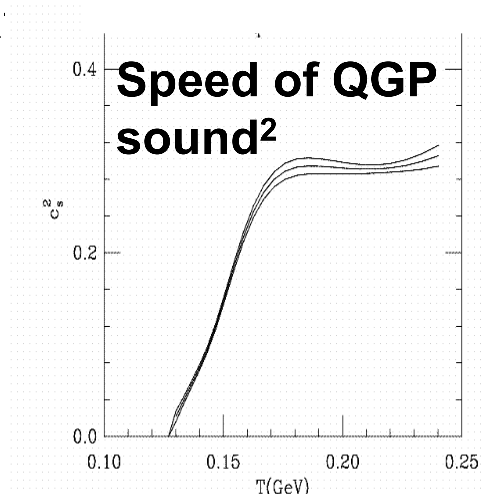
What is the Light Cone structure of nuclei?

- Small x quark and gluons spin structure of A=1
- High energy limit of nuclear wave function:
  - Gluon saturation and the CGC
- Non-perturbative QCD structures:
  - Baryon Junctions , Glue Balls, Penta-quarks



What is the Physics of Deconfinement ?

- High energy density limit of matter: **sQGP** -> **wQGP**
- Melting point of physical vacuum Gluon Condensa
- Latent Heat and the Entropy step through T_c
- Speed of sound of sQGP
- Correlations and Quasiparticles above T_c



Gyulassy DOE 4/5/05

Fundamental Questions about the Strongest Force of Nature that Ultra-relativistic nuclear collisions (p+p, p+A, B+A) may answer

Can Chiral symmetry be restored ?

- Melting point of the physical vacuum: Chiral condensate
- Metastable Disordered Chiral Condensates ?
- Vector meson ρ, ψ, ... spectral functions near T_c
- Axial anomaly $\eta' \; \eta \; \pi$, CP θ–vacua

Non-extensive Thermodynamics of Finite sQGP ?

- Hydrodynamics coupled to pQCD power law tails
- Radiative transport (as in HEDP plasma, Supernova)
- Critical Self similar flows, turbulence
- Chaos and fractal branching in Yang Mills

Fundamental Questions about the Strongest Force of Nature that Ultra-relativistic nuclear collisions (p+p, p+A, B+A) may answer

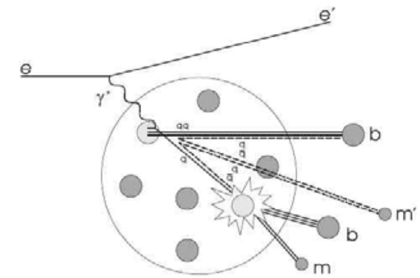
Dynamics of Confinement and Hadronization

q and g ⟶ h Fragmentation in vacuum vs cold and hot QCD matter

qq vs qqq Recombination and the baryon meson anomaly

$$sQGP \Rightarrow \quad Q\bar{Q}P \quad \Rightarrow \quad \pi,\gamma,\bar{p},\psi,\ldots$$

(?constituent quark plasma?)



Relaxation and Transport properties of sQGP

CGC ⟶ sQGP equilibration ? Non-abelian instabilities?

Elastic , Ionization, and Inelastic stopping power

Shear and Bulk viscosity, Thermal conductivity

* adS/CFT and Unitary bounds at **g^2N_c** $\longrightarrow \infty$
* Strongly coupled Abelian plasmas, Li-Li , He-He systems
  Feshbach resonances , Unitary Limited Scattering lengths

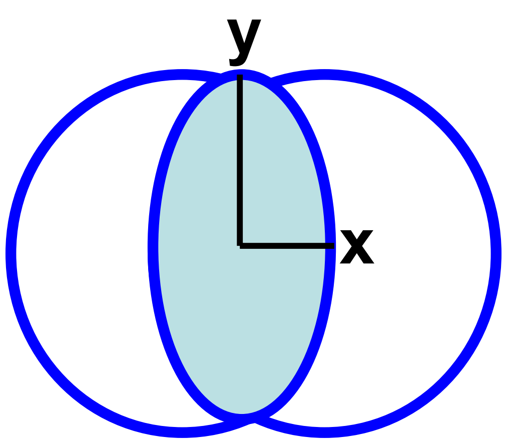
Bulk Collective Flow as Barometer of QCD matter

$$\partial_\mu T^{\mu\nu} = \partial_\mu \{u^\mu u^\nu (e(T) + P(T)) - g^{\mu\nu} P(T)\} = 0$$

QCD EOS

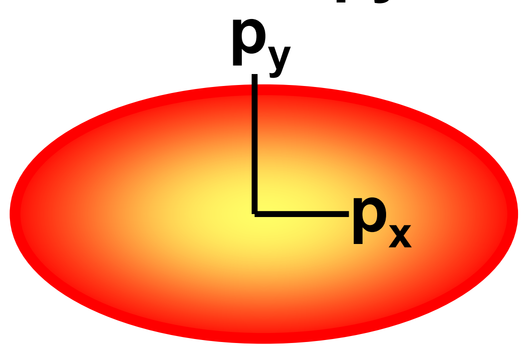
W. Greiner, H. Stocker (1974)
P. Kolb, U. Heinz et al (2000)
D. Teany, E. Shuryak
T. Hirano, Y. Nara

Initial *spatial* anisotropy



$\partial_\mu T^{\mu\nu}(x) = 0$

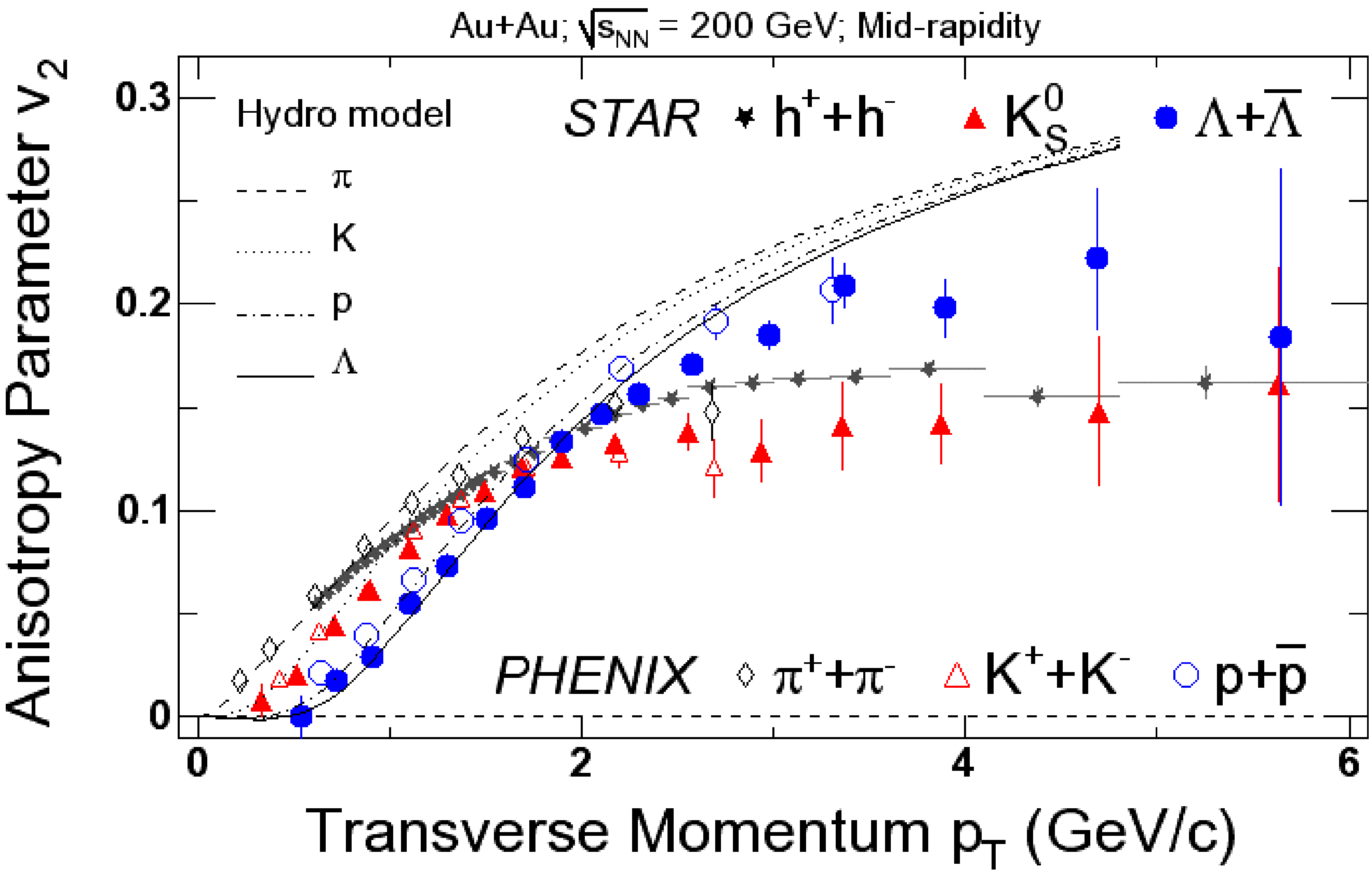
Final *momentum* anisotropy



Elliptic Flow

$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y, p_T)\{1 + 2 v_2(p_T)\cos(2\phi) + \cdots\}$$

sQGP Fingerprint at RHIC = Fine Structure of elliptic flow

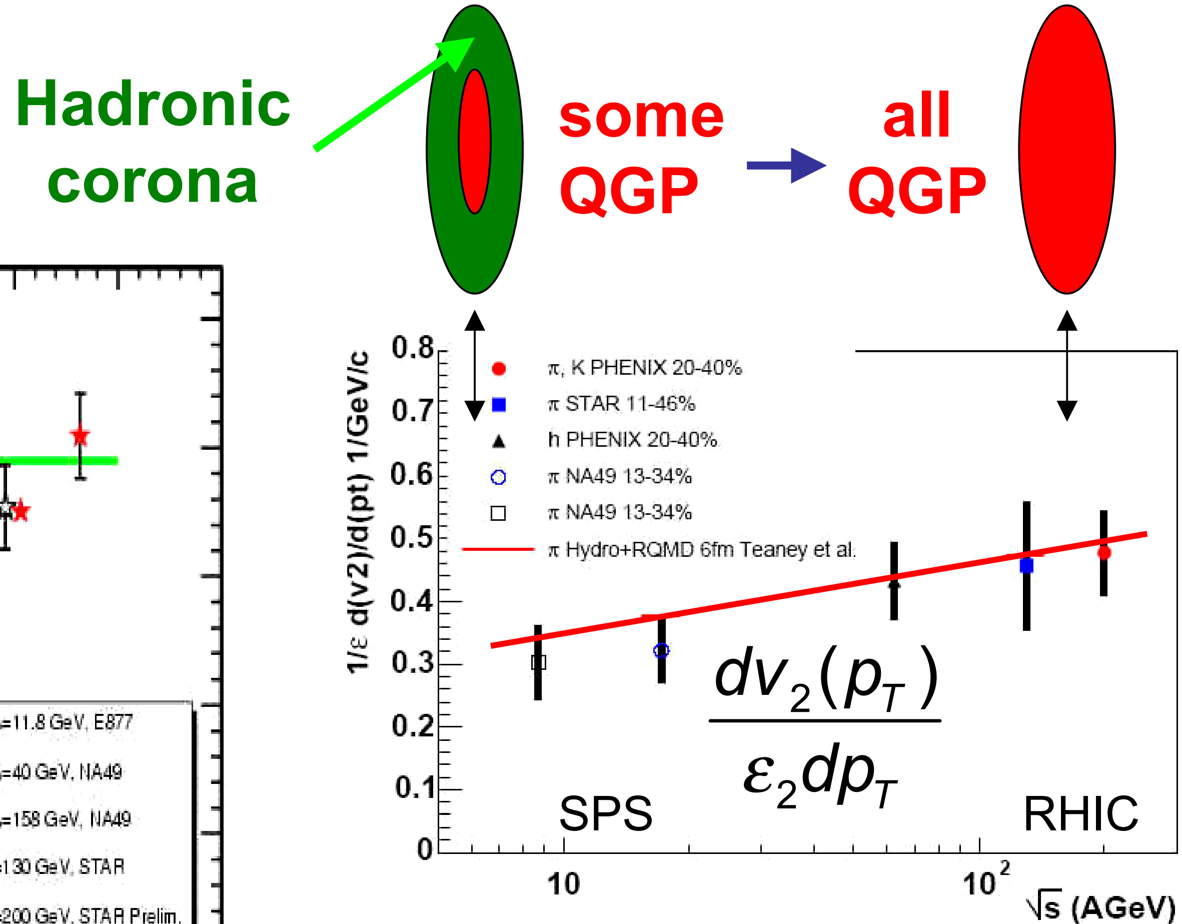


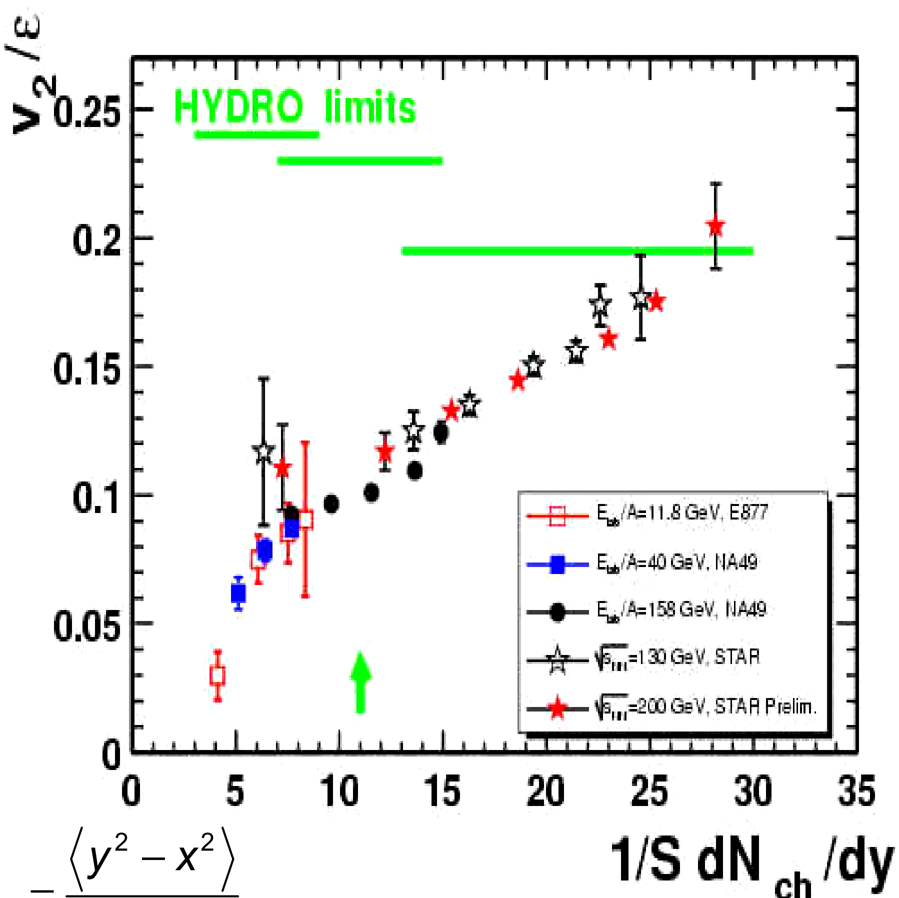
Bulk P_{QCD} Hydro

qqq Coalescence

pQCD Jets

Failure of hydrodynamics at lower SPS energies due to Ordinary highly *dissipative* Hadronic Corona





$$\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Breakdown of Hydrodynamics in Hadronic Phase explains excitation function of $v_2(p_T,\sqrt{s})$

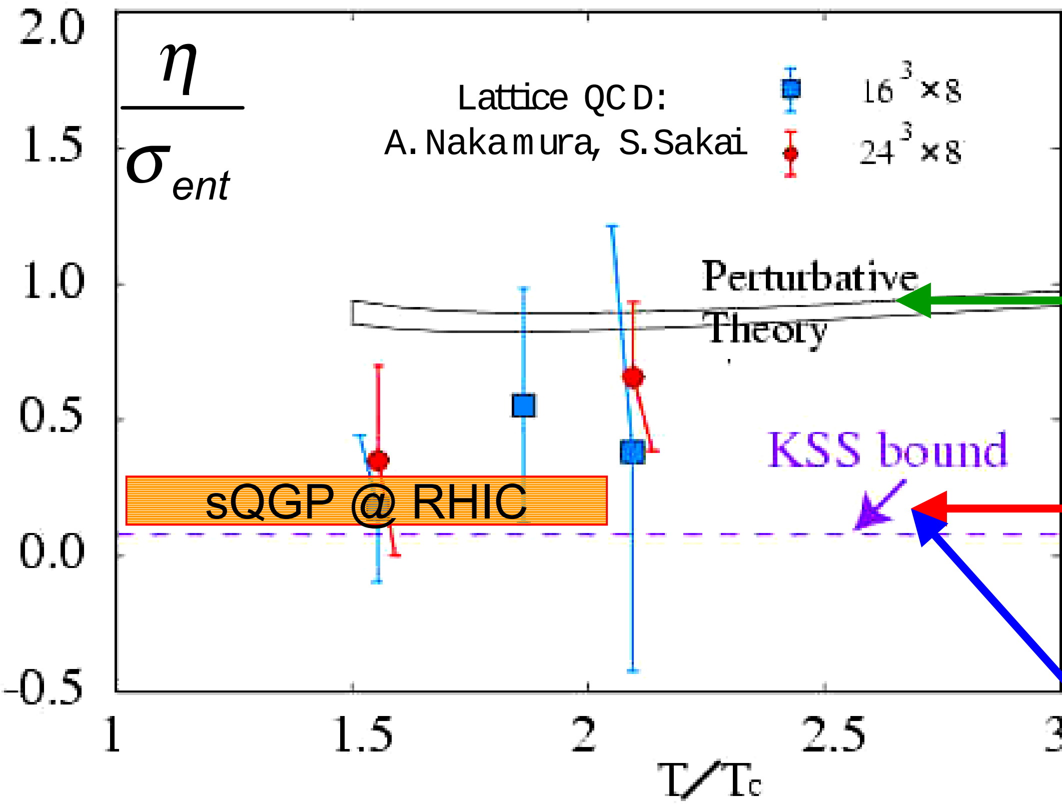
Mystery of small sQGP Viscosity

Lattice QCD *vs* pQCD *vs* AdS/CFT *vs* $\Delta x \Delta p \geq \hbar$

Shear Viscosity

$$\eta = \tfrac{1}{5}(\varepsilon + P)\lambda = \sigma_{entropy}\left(\frac{T\lambda}{5}\right)$$

Kittel: Kinetic Theory



$$\frac{T\,\lambda_{pQCD}}{5} \approx 1$$

pQCD

$$\left(\frac{\eta}{\sigma}\right) \geq \frac{\hbar}{4\pi}$$

AdS / CFT

N = 4 SUSY

$g^2 N_c \to \infty$

$$\frac{T\lambda}{5} \geq \frac{\hbar}{15}$$

$\Delta x = \lambda$

$\Delta p \approx 3T$

N=4 SUSY: Kovtun,Son,Starinets (2004)

Danielewics, MG (1985)

Importance of controlled A+A Initial Conditions

$\boxed{\partial_\mu T^{\mu\nu} = 0}$ Is a 1-to-1 map from Initial → Final

How is the sQGP created ?

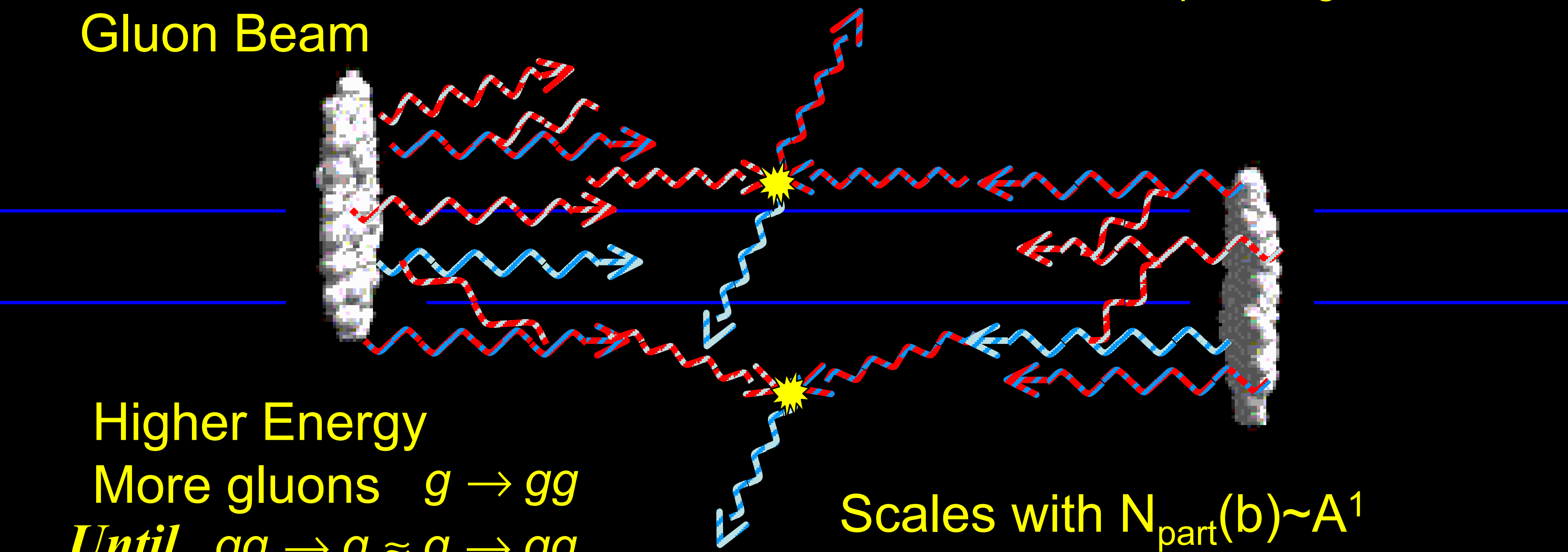
The CGC source of sQGP

sQGP Formation via GCG

High Energy Nucleus
Is equivalent to a
Weizsacker-Williams
Gluon Beam

Scales with $N_{BC}(b) \sim A^{4/3}$

$g + g \rightarrow g + g \qquad p_T > Q_s(x,A)$



Higher Energy
More gluons $\quad g \rightarrow gg$
Until $\quad gg \rightarrow g \approx g \rightarrow gg$

Scales with $N_{part}(b) \sim A^1$

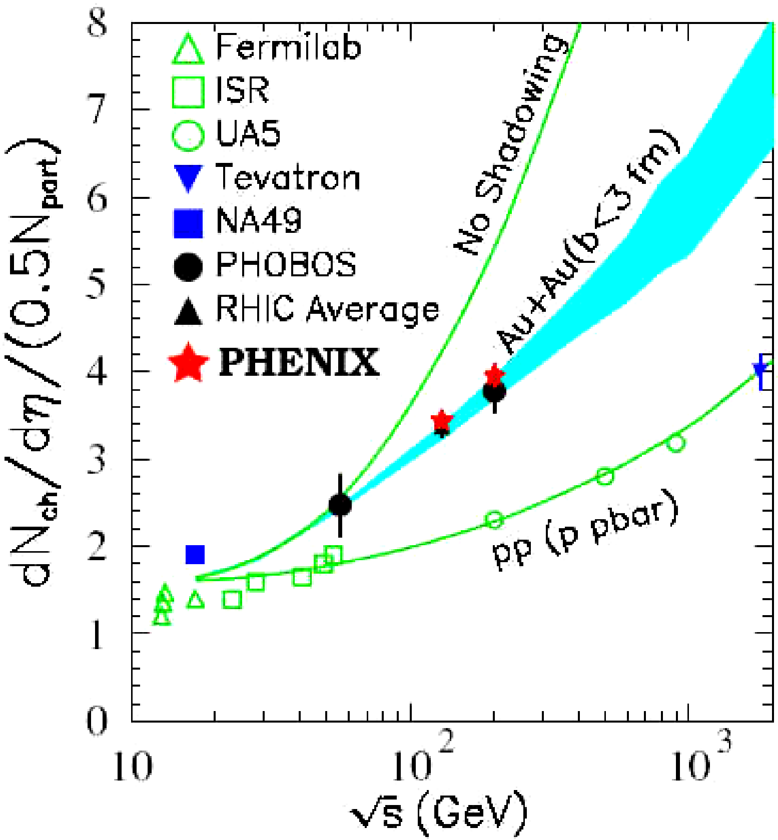
$g' + g' \rightarrow g \qquad p_T < Q_s(x,A)$

Color Glass Condensate Saturation Scale

$$Q_s^2(x,A) \approx 1\,\text{GeV}^2 \left(\frac{10^{-4}}{x}\right)^{0.3} A^{0.3}$$

Global Evidence for saturating CGC initial state at RHIC

$$Q_s^2(x,A) \approx 2\,\mathrm{GeV}^2 \left(\frac{10^{-2}}{x}\frac{A}{200}\right)^{0.3}$$



Gluon Saturation below k_T < Q_s

Limits Rapid Growth of pQCD mini-jets

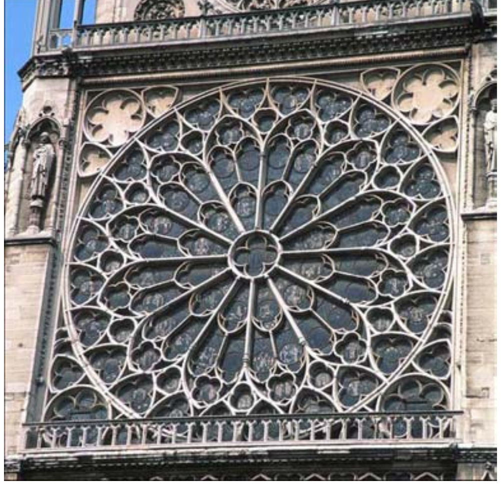
Corresponds to Deep Gluon Shadowing in x<0.01 region

$$N_{ch} = \rho_s(Q_s)\,A + \rho_H(Q_s)\,A^{4/3}$$

RHIC data prove Q_s varies with s and A as predicted

Nuclear Glue Structure RHIC vs LHC

RHIC is the sQGP machine with a partial view of CGC



CGC at RHIC

$$\frac{dN_g}{dy} \approx c\,\frac{Q_s^2 R^2}{\alpha_s(Q_s^2)}\left(1-\frac{2Q_s}{\sqrt{s}}e^{|y|}\right)^4$$

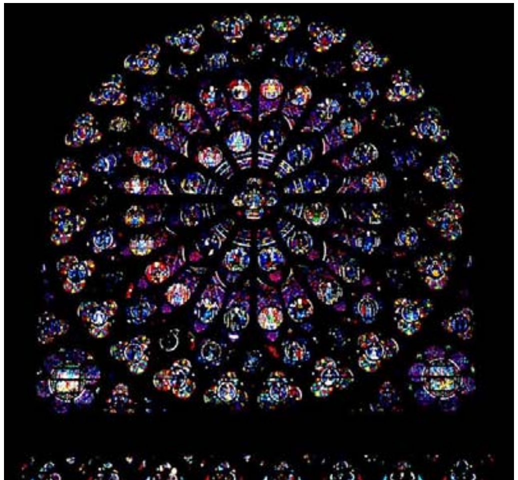
Kinematically Limited at y = 3

$$Q_s^2(x,A) \approx 2\,\mathrm{GeV}^2\left(\frac{10^{-2}}{x}\frac{A}{200}\right)^{0.3} \Rightarrow \begin{cases} \xrightarrow[y=3\ p_T=2]{\mathrm{RHIC}} 5\,\mathrm{GeV}^2 \\ \xrightarrow[y=0\ p_T=2]{\mathrm{LHC}} 5\,\mathrm{GeV}^2 \\ \xrightarrow[y=3\ p_T=2]{\mathrm{LHC}} 14\,\mathrm{GeV}^2 \end{cases}$$

$$\frac{dN_g}{dy} \approx c\,\frac{Q_s^2 R^2}{\alpha_s(Q_s^2)}$$

Kinematics Free at y ≤ 3

CGC at LHC



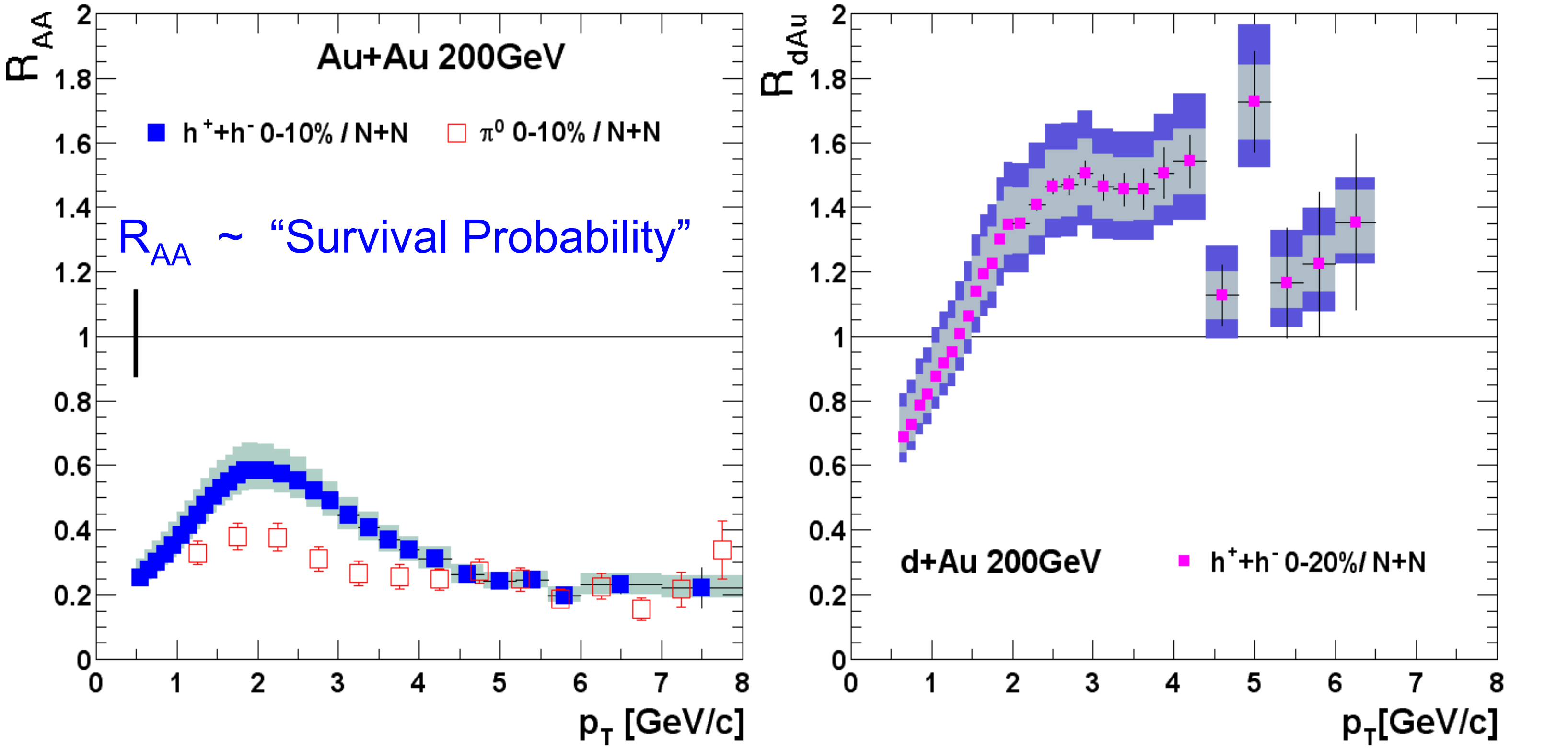
LHC is the CGC machine with a partial view of sQGP

THE Unique advantage of RHIC is the proven ability to perform

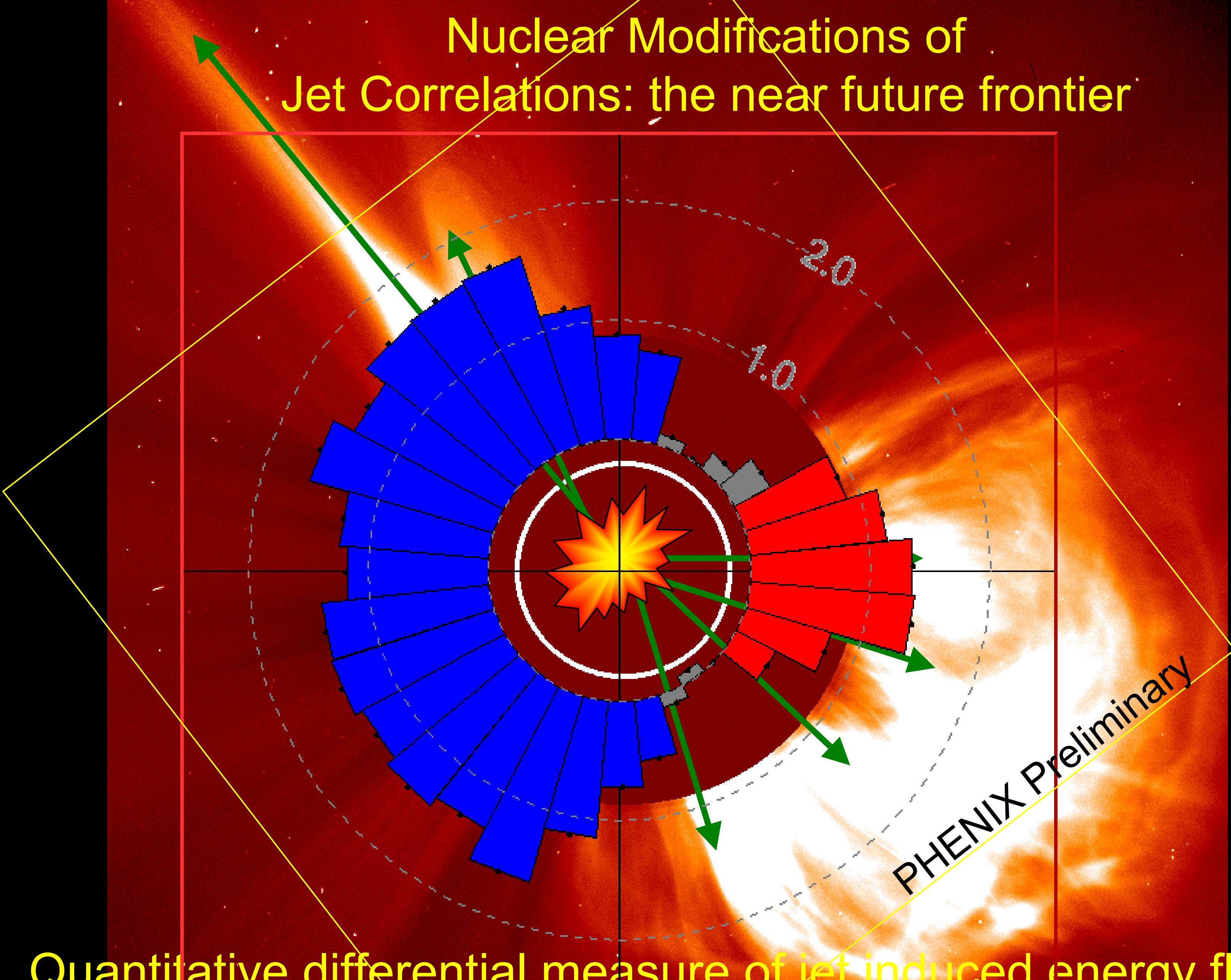
Dedicated Control p+p and p+A as well as B+A experiments

Required to sort the competing novel physics of sQGP from its CGC source

Nuclear Modification Factor $R_{BA}(p_\perp) = dN^{BA\to\pi} / T_{BA}(b)\, d\sigma^{pp\to\pi}$



Nuclear Modifications of Jet Correlations: the near future frontier



Quantitative differential measure of jet induced energy flow

Fuqiang Wang (STAR) RBRC Jets05 3/10/05

RHIC has already proven to be the most productive and bountiful Nuclear Physics discovery machine ever!

- There is overwhelming evidence that novel states of QCD matter are formed in Au+Au with unique properties never seen before

- Data prove that the original 1975 weakly coupled wQGP paradigm based on asymptotic freedom is incomplete near T_c
  Forcing a shift to a new sQGP paradigm that is **now under construction**

- In next 5 years RHIC is completely ready to move beyond the discovery phase (based on global and single inclusive measurements)

- To the comprehensive **quantitative phase** based on new diagnostic probes
  - Heavy quarks, Direct photons, and Lepton pairs
  - Differential multi-particle correlations

- On the 5-10 year term, more precise and detailed characterization of the physics will certainly require much more pp,pA,AA with significant increase of luminosity and new detector systems. (e.g. gamma-tagged 3D Jet Tomography)

My Answer to the "RHIC during LHC Era" Question

RHIC and LHC both have **unique** and **complementary** discovery potentials to answer Key questions about the nature of the strongest force known, QCD

THE unique advantage of RHIC is that it has the proven record of physics discovery *and* the "good fortune" that the CGC provides a well defined initial state with an unobstructed high pT window on the sQGP properties at mid-rapidity.

We know this because of RHIC performed 4 independent dedicated Control p+p and p+A experiments required to sort out the non-linear initial and non-linear final state physics

In contrast J/Psi suppression data are still incomplete at SPS Because ***not enough*** p+A control experiments were approved.

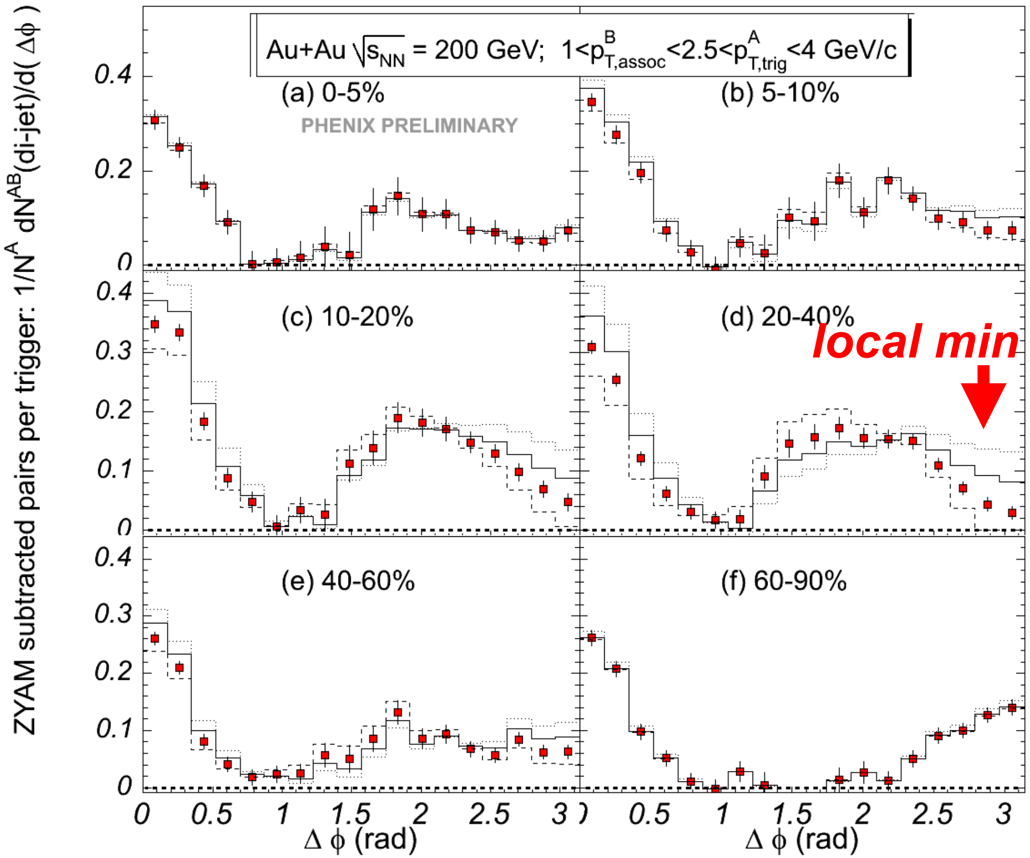
At LHC, dedicated **p+p and p+A control experiment** will also be required Since the CGC will dominate many sQGP observables at all rapidities.

Appendix: extra Slides Not Shown

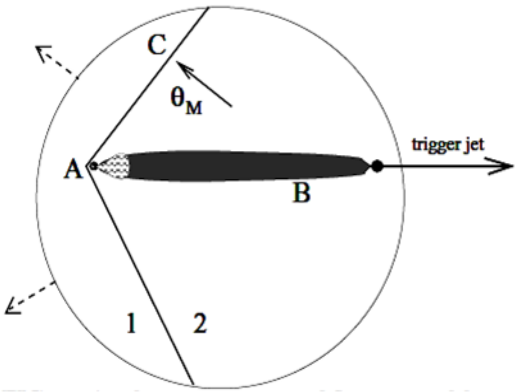
- Often used Short Hand:
  - QCD = Quantum Chromodynamics
  - wQGP = weakly couple Quark Gluon Plasma
  - sQGP = strongly coupled Quark Gluon Plasma
  - CGC = Color Glass Condensate
  - AdS/CFT=Maldecena conjectured duality between

  weak gravity in 5D anti-de Sitter space and Infinite coupled conformal N=4 Supersymmetry field theory in 4D
  - TOE = The Theory of Everything

Associated jet-pair distributions



Wake effect or "sonic boom"?



Crash Course on Dissipative Hydrodynamics:

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = \left\{(\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}\right\} + \tau^{\mu\nu}$$

Flow velocity field u^μ(x,t) and temperature field T(x,t)

1+1D Hubble

$$\boxed{\frac{d\epsilon}{d\tau} + \frac{1}{\tau}(\epsilon + p) = (\tfrac{4}{3}\eta + \xi)/\tau^2}$$

Bjorken

sound

$$\boxed{\omega = u_s q - \frac{i}{2}\frac{1}{\epsilon + P}\underbrace{\left(\zeta + \frac{4}{3}\eta\right)}_{\text{Damping}} q^2, \qquad u_s^2 = \frac{\partial P}{\partial \epsilon}}$$

Shear viscosity

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\boldsymbol{x}\, e^{i\omega t} \langle [T_{xy}(x), T_{xy}(0)] \rangle$$

Kubo

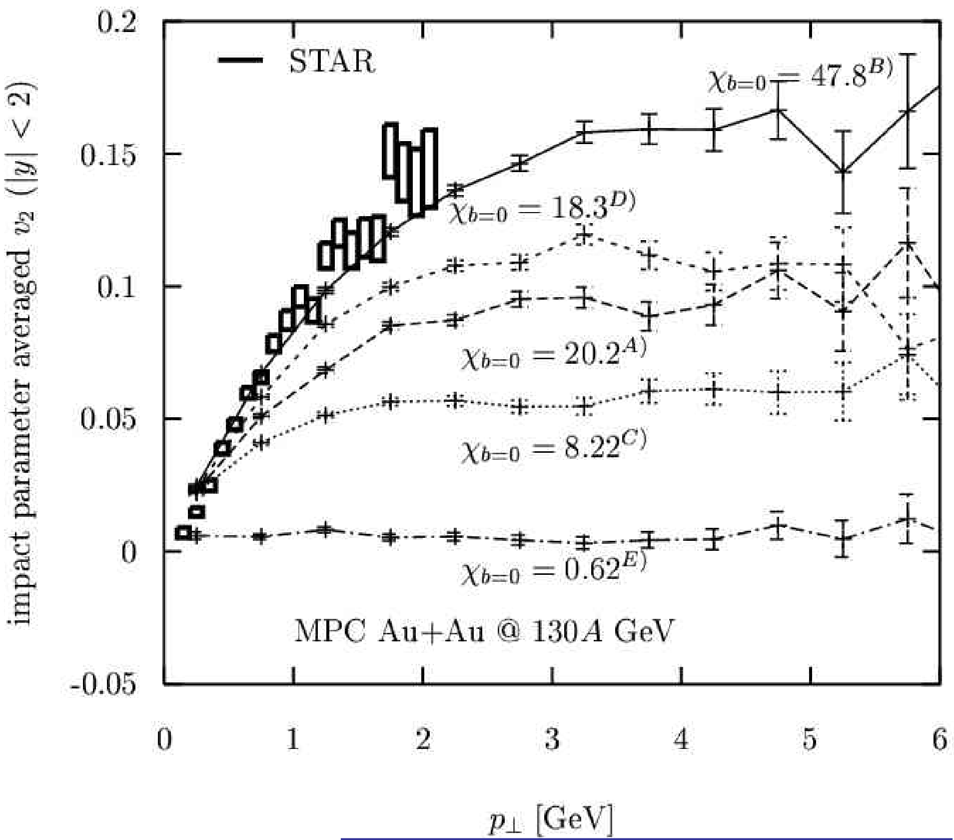
$$\eta = \tfrac{1}{5}(\varepsilon + P)\lambda = \sigma_{\text{entropy}}\left(\frac{T\lambda}{5}\right)$$

Gas kinetic theory

Why sQGP must be almost a perfect fluid !

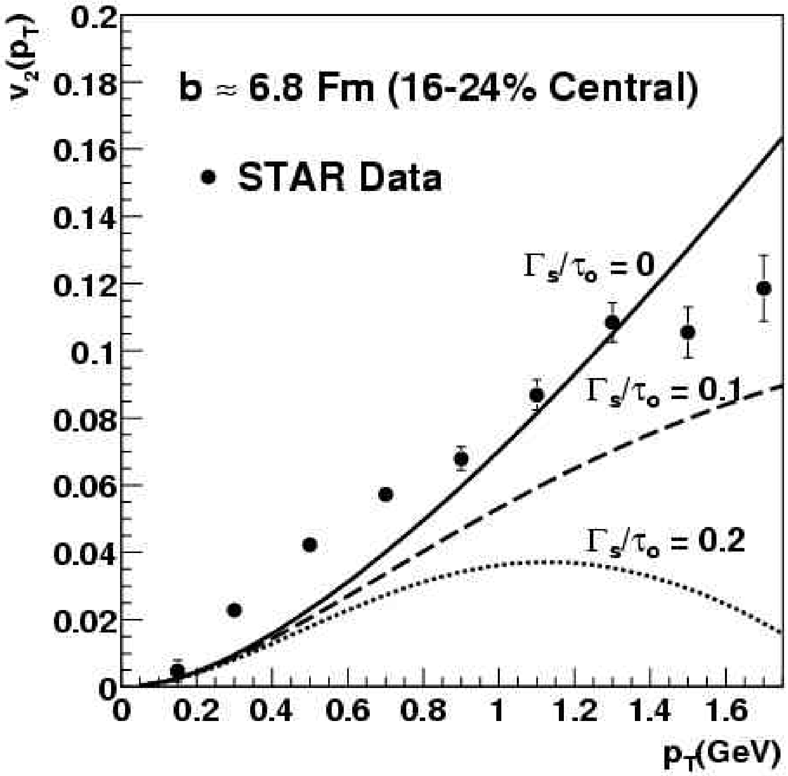
Gluon Transport

D.Molnar, MG (01)



Navier-Stokes

D.Teaney (03)



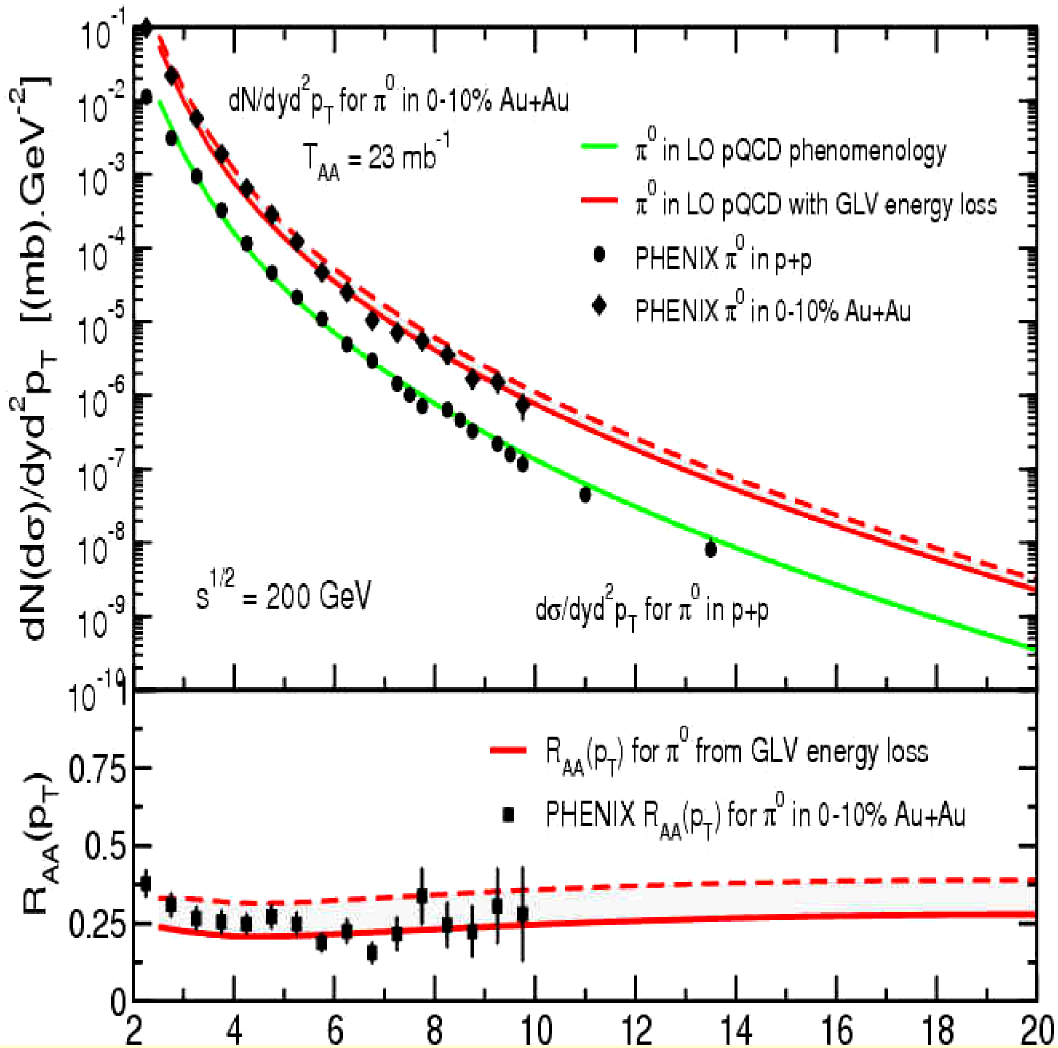
Opacity $\boxed{\chi = \int d\tau\, \sigma\, \rho \approx \frac{dN_g}{dy} \frac{\sigma_g}{\pi R^2}}$ **must be ~ 10 x wQGP**

Absolute Scale

Jet Tomography

Adil, Vitev, MG (2005)

$\boxed{dN_g/dy = 900\text{-}1200}$



p_T GeV

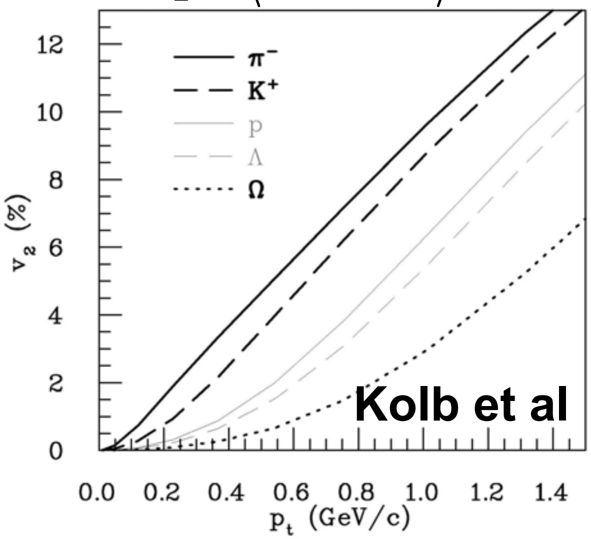
$$dN_{AB\to p} = T_{AB} \otimes \left(f_{a/A} \otimes f_{b/B}\right)^{shad}_{\Delta k_T} \otimes d\sigma_{ab\to c} \otimes P(\Delta E) \otimes D_{\pi/c}$$

FIG. 5: Absolute inclusive π^0 invariant cross section data at RHIC on *pp* and 10% central AuAu from PHENIX compared to LO pQCD baseline for pp and GLV quenched for AuAu.

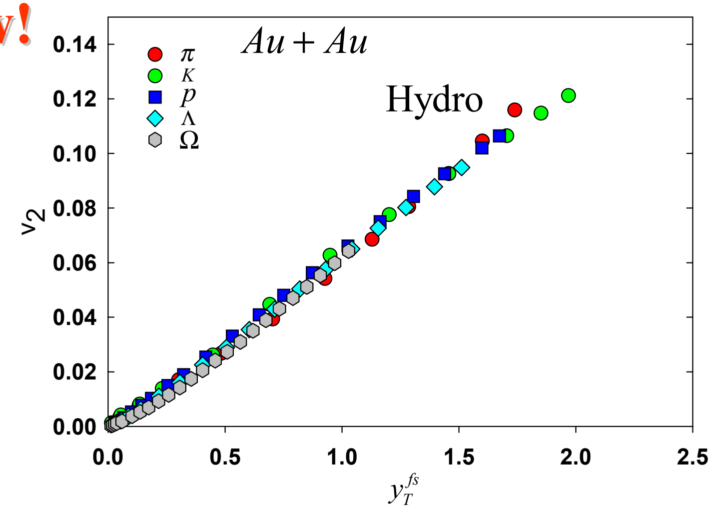
Hydro scaling of Fine structure at RHIC

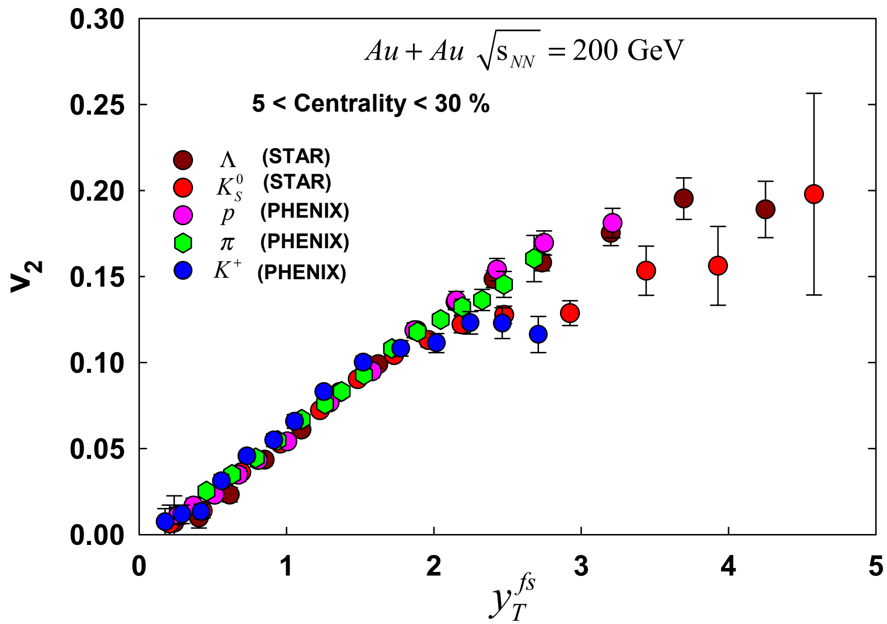
Compelling evidence for novel hydrodynamic collective flow!

$$v_2 = \langle Cos(2\phi) \rangle$$



Scaling hydro





$$p_T \rightarrow y_T = \sinh^{-1}(p_T / m)$$

Buda Lund Hydro Model:

$$v_2 \sim \frac{k_1}{T_0} \times y_T^2 m \left(1 + \frac{k_2}{k_1}\frac{T_0}{m} + \frac{k_3}{k_1}\left(\frac{T_0}{m}\right)^2 + .. \right)$$

$$y_T^{fs} \equiv k_m \times y_T^2 m$$